SUPERCONDUCTING PLANAR UNDULATOR DEVELOPMENT IN THE UK

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Abstract

Superconducting undulators promise higher peak fields on axis than any other technology but they are still not a mainstream solution for 3rd or 4th generation light sources. A team within the UK is developing the design of a short period, narrow aperture, superconducting undulator that is planned to be installed and tested in the Diamond Light Source (DLS) in 2014. This paper will describe the main parameters of the undulator and the key design choices that have been made. Recent progress is then described in the areas of magnet modelling, mechanical design, cryogenic design, and prototyping. Finally, the next steps are described.

INTRODUCTION

The UK has developed considerable superconducting undulator expertise over recent years with the extensive design and prototyping of helical undulators for the International Linear Collider (ILC). These short period, relatively high field magnets are extremely challenging and the successful manufacture and test of a 4 m long helical undulator cryomodule was a major milestone for the ILC project [1]. We are now applying the skills and knowledge gained from this helical undulator magnet project in order to develop a planar superconducting undulator that is suitable for 3rd and 4th generation light sources. In particular we aim to design, fabricate, and test a 2 m long superconducting planar undulator that will then be installed into DLS in 2014.

Parameters

The key parameters of the undulator have been developed in collaboration with DLS to ensure that the prototype will be compatible with installation into that facility with little disruption to the existing users. In particular the magnet gap has been determined by ensuring that the new fixed gap aperture set by the undulator is equivalent to the existing lowest fixed gap aperture currently installed. The current limiting fixed gap vertical aperture is 8 mm over a 5 m long straight section. Scaling this down for a 2 m long magnet installed in the centre of a 5 m straight defines the vertical aperture to be 5.4 mm. This should ensure that the impact on the operation of DLS is negligible in terms of reduced aperture to the electron beam.

To select the undulator period and field strength a number of criteria were considered. These included:

- Maximising the flux and brightness at high photon energies (25 and 40 keV)
- Minimizing the undulator harmonic at these high photon energies
- The requirement to provide continuous tunability from 6.5 keV and higher

The selected optimum undulator parameters are summarized in Table 1. It is estimated that if these parameters are achieved the users will receive an increase in flux of ~15 times and brightness of ~20 times at 40 keV when compared to a standard in-vacuum undulator.

Table 1: Undulator Parameters

Magnet Length	2.0	m
Period	15	mm
Peak Field on Axis	1.29	T
K	1.8	
Required Phase Error	<3	°
Magnet Pole Gap	7.4	mm
Vertical Beam Aperture	5.4	mm
SC Wire Dimensions	0.765 x 0.375	mm
Operating Current	480	A
SC Material	NbTi	
Cu:SC Ratio	0.9:1	
Peak Field in the SC	3.3	T
Turns per Layer	6	
Number of Layers	11	
Magnet Operating Temperature	1.8	K
Beam Tube Temperature	12 – 16	K

Design Choices

Despite the clear advantages of superconducting technology in the generation of very high magnetic fields, the generation of a relatively modest field (1.29 T) in a magnet with 15 mm period and magnet pole gap of 7.4 mm using this technology is extremely challenging. The SC material must be operated close to the quench limit to achieve these fields, leaving little safety margin. We have made a number of design choices in order to try to ensure that the undulator will achieve the design field whilst simultaneously maximising the safety margin.

The first design choice we have made is to provide an intermediate temperature (12 to 16 K) vacuum vessel for the electron beam. This vessel will be able to cope with the anticipated beam heating due to resistive wall wakefields and uncollimated synchrotron radiation from the upstream dipole. This vessel will be thermally isolated from the undulator magnet with no direct points of contact allowed. A major consequence of this choice is that a full allowance of 2 mm is needed between the vertical beam aperture and the magnet pole gap to provide space for the vacuum vessel walls and thermally isolating gap.

The second design choice is that we aim to construct the magnet to within very challenging engineering tolerances in order to remove any requirement for magnet shimming. Numerous shimming proposals have been made for similar superconducting undulators but they all tend to have a negative impact in terms of reducing the peak field on axis or adding substantial complexity to the cryomodule. We have carefully assessed the engineering tolerances which are required in order to maintain the phase error to within ~3° and we have based our design on achieving these values [2].

The third design choice we have made is to operate the magnet itself at 1.8 K rather than the more usual 4.2 K. This reduction in temperature provides significant extra safety margin but simultaneously makes the cryogenic system more complex. The magnet will be stand-alone cryogenically, with all the cooling being provided by a number of dedicated cryocoolers. In order to demonstrate that 1.8 K can be achieved and maintained we will fabricate and test the cryogenic system of the undulator cryomodule in isolation first, with a dummy heat load to represent the undulator.

DESIGN PROGRESS

Magnet Modelling

Significant magnet modelling was carried out at the start of this project in order to compare the possible alternative geometries, materials, and winding arrangements [2]. That study concluded that rectangular NbTi at 1.8 K was the optimum choice for the undulator in terms of operating margin and ease of fabrication. Since then significant further optimisation has been carried out as part of the final parameter selection (in particular the field, gap, and period). A number of 3D models were run using Vector Fields software [3] covering a range of periods from 13 to 17 mm and magnet gaps from 5 to 10 mm. The peak field for all these models, at a fixed operating margin of 10%, is plotted in Figure 1. An empirical equation has been fitted to the results to help with estimating the possible peak fields at intermediate gap and period values. Note that the scatter in the plot is largely due to the discrete nature of the model in terms of maintaining an integer number of wires per layer.

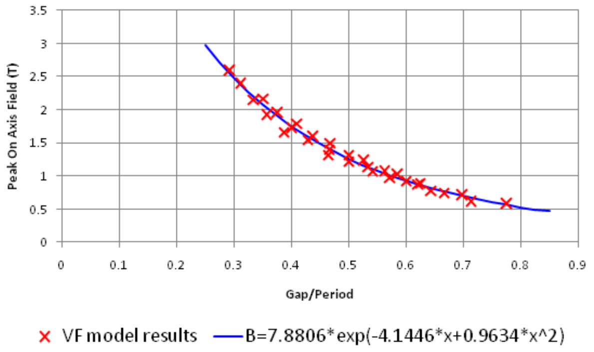

Figure 1: Peak field on axis as a function of magnet gap/period. The blue line is an empirical fit with equation as shown in the legend.

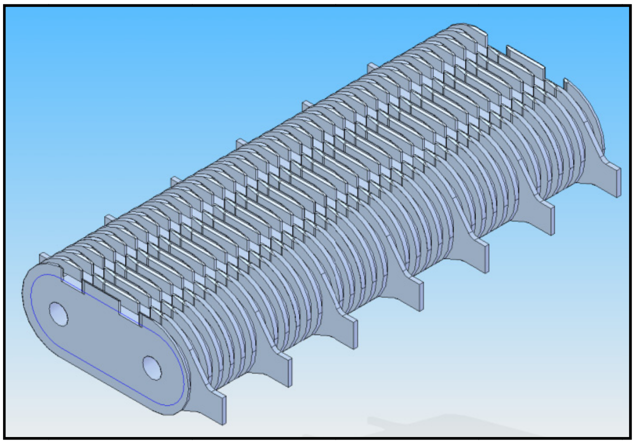

Figure 2: Isometric view of a magnet former, length 285mm.

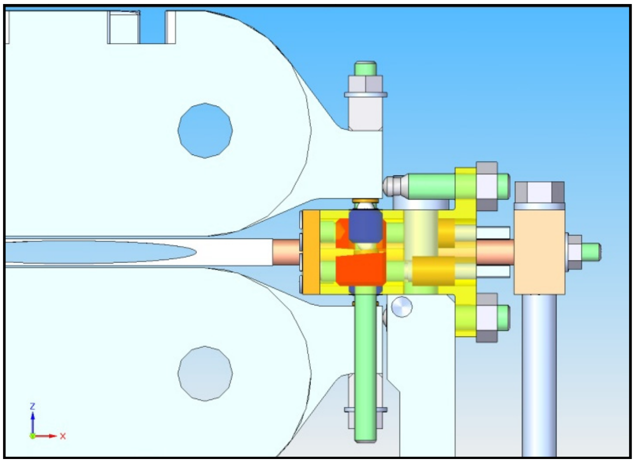

Figure 3: End view of magnet assembly showing optical-style adjustable mounting system.

Mechanical Design

Manufacturing a full 2 m solid magnet is prohibitively expensive to the tolerances required so, instead, shorter sections will be machined (see Figure 2) and wound before being positioned and aligned onto a structural beam, relative to an external datum, using an optical-style mounting system (see Figure 3). Each magnet section is placed on height-adjustable screw jacks at 3 corners and, using a laser level, will be manipulated until parallel with the datum plane as required. The whole assembly will then be hung from the outer cryostat using adjustable rods; these create externally measureable reference points with which the position of the magnet can be determined and thus aligned to the beamline.

Cryogenic Design

The cryogenic design for the superconducting undulator is based on the use of closed cycle refrigerators. In order to achieve the required critical current from the superconductor the bath temperature needs to be approximately 2 K. This is achieved by using a continuous flow cryostat in the central turret. A series of heat exchangers, linked to the refrigeration stages, returns the circulating helium to the bath where it is expanded through a JT valve. For the temperature specification 16 mbar will be required on the effluent side of the helium expansion. In order to meet the heat loads a minimum helium flow of 10 mg/s is required – this corresponds to a stp flow of about 3.4 litres/min. This circulation will be provided by a Leybold SC30D scroll pump. Cooling pipes through the undulator deliver the liquid helium to the cold mass of the magnet. The main two stage refrigerator also provides intermediate cooling for the High Temperature Superconducting (HTS) current leads. The design allows for the turret and 2 K continuous flow cryostat system to be tested off the main undulator cryostat prior to final integration.

The beam tube will be operated at 12 to 16 K – at this temperature the maximum residual resistance ratio for the material is achieved and there is little benefit in cooling to lower temperatures. The load on the beam tube is dominated by the wakefield heating from the beam and could be as high as 40 W. There is much uncertainty in this figure and so a dedicated test cryostat will be installed into DLS in November 2011 in order to make systematic measurements of the actual heat loads due to the electron beam. Cooling of the beam tube is achieved by the use of two closed cycle refrigerators (Sumitomo SRD415) one at each end of the undulator. The first stage of these refrigerators also cools the ends of the 55 K radiation shields. The beam tube also partly acts as a thermal radiation shield for the magnet system.

The current leads will be composed of copper from room temperature to 55 K and then HTS from 55 K to 4 K. From there NbTi will be used into the main coil. The heat load on the two-stage cryocooler in the turret is dominated by the heat leak down the current leads – this will be approximately 34 W.

Trial Windings and Prototypes

A small trial section of the magnet was produced using tightly tolerance plates. These plates were put together and wound, this allowed us to try out different insulators and to check the winding pattern. This test piece was later sectioned and that confirmed that the accuracy and pattern of the winding was good. We also tested the insulation used between the windings and the former. The insulation was tested both for electrical and mechanical properties. The assembly and accuracy achieved with these plates has influenced the design of the magnet significantly.

A ~300 mm prototype of the magnet will be produced to the best accuracy that can be achieved using conventional engineering techniques. This will be wound and tested to give us a better understanding of the achievable tolerances of the final magnets. The programme for the manufacturing will be set for a 3 axis CNC milling machine. The prototype will be measured at different stages of the manufacture to ensure its accuracy.

FUTURE PLANS

The next step will be the manufacture and test of a ~300 mm long prototype undulator. This will be used to confirm the mechanical and magnetic design, the winding technique, and the potting arrangement. Comprehensive mechanical measurements will be carried out on the former and the complete magnet to check whether the required tolerances have been achieved.

This short prototype will also be measured magnetically in a vertical test cryostat. The requirements of the magnet measurement system have recently been established and these are now being used in the detailed design phase of the measurement system. A transverse array of Hall probes will be used so that the magnetic field can be measured simultaneously across the horizontal plane of the undulator, providing useful information about the multipole components. The calibration requirements of these Hall probes is being carefully considered now.

In parallel to the short prototype, the cryogenic system will also be assembled allowing the 1.8 K system to be proven offline. This cryogenic system will use the actual services turret of the final cryomodule, providing as complete a test as possible and also minimising the future effort required during assembly of the complete system.

Once the prototype magnet and cryogenic system have been fully proven construction of the final magnet will commence. The current plan assumes installation of a fully tested undulator into DLS in 2014.

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